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RESEARCH PAPER

Preserving biodiversity under current and future climates: a case study

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ABSTRACT

Aim The conservation of biological and genetic diversity is a major goal of reserve systems at local, regional, and national levels. The International Union for the Conservation of Nature and Natural Resources suggests a 12% threshold (area basis) for adequate protection of biological and genetic diversity of a plant community. However, thresholds based on area may protect only a small portion of the total diversity if the locations are chosen without regard to the variation within the community. The objectives of this study were to demonstrate methods to apply a coarse-filter approach for identifying gaps in the current reserve system of the *Psuedotsuga menziesii* (Douglas-fir) forest type group based on current climatic conditions and a global climate change scenario.

Location Western United States.

Method We used an ecological envelope approach that was based on seven bioclimatic factors, two topographic factors, and two edaphic factors. Multivariate factor analysis was then used to reduce the envelope to two dimensions. The relative density of habitat and protected areas were identified in each part of the envelope based on the current climate and potential future climate. We used this information to identify gaps in the reserve system.

Results Although the protected areas occurred in all parts of the envelope, most existed in colder and drier areas. This was true for both the current climate and potential future climate.

Main conclusion To protect more of the ecological envelope, future conservation efforts would be most effective in western Oregon, north-western Washington, and north-western California.

Keywords
Coarse-filter, conservation, Douglas-fir communities, ecological envelope, factor analysis, global climate change, North America, *Pseudotsuga menziesii.*

INTRODUCTION

Setting aside protected areas is a key to maintaining biological diversity. The extent of area in protected status is an international issue and is addressed, for example, as part of the Montréal Process for the Conservation and Sustainable Management of Temperate and Boreal Forests (Montreal Process, 1995). The classic definition of biological diversity (biodiversity) is 'the variety and variability among living organisms and the ecological complexes in which they occur' (Office of Technology Assessment, 1987). It may be viewed in a hierarchical framework where levels include genes, species, populations, communities, ecosystems, and landscapes (Noss, 1990). In the absence of detailed knowledge of actual diversity, Scott *et al.* (1993) suggest that protecting a plant community may be a surrogate for protecting the diversity of components associated with that community. In other words, protecting a plant community also protects the genes, species, and populations within that community.

Miller (1984) proposed that at least 12% of the world's land area should be reserved in order to maintain biodiversity. Although 12% may be adequate to preserve biodiversity in some communities, other communities may require a greater or smaller percentage (Noss & Cooperrider, 1994; Soulé & Sanjayan, 1998). Because maintaining biodiversity requires protection across a plant community's range (Scott *et al.*, 2001a), a better guide may be to set protection thresholds based on the variation of the plant community. If two plant communities have the same areal extent but one community has little variation and the other community has a large amount of variation, then the community with the larger amount of variation will require reserving a larger proportion of its geographic range to achieve the same level of effective protection.

The geographic range of a community can be described as an ecological envelope defined by topographic, bioclimatic, and edaphic gradients (Akin, 1991). An ecological envelope may have several parts. The geometric centre or core of the envelope can represent the topographic, bioclimatic, and edaphic conditions most favourable to the community. Conversely, the edge of the envelope represents the marginal habitats where the community exists. The ecological envelope approach has been used for several applications. For example, Iverson & Prasad (1998) used information on climate, soils, land use, elevation, and species assemblages to predict how the current geographic distribution of 80 tree species may change in response to climate change. Delcourt & Delcourt (1998) classified *Picea abies* stands by gradients of elevation and latitude to identify climatic and edaphic limits of the species. Huntley *et al.* (1995) used climate response surfaces to model the present and potential future ranges of eight European higher plant species. The models were based on locally weighted regression, which assigned a probability of each species' occurrence based on mean temperature in the coldest month, growing degree-days, and the ratio of actual to potential evapotranspiration. With respect to preserving biodiversity, the size and shape of the ecological envelope dictates what habitats should be protected and where the protection should occur. This is the coarse-filter concept proposed by Hunter *et al.* (1988).

The motivation for the course-filter approach is that the distribution of reserves should be influenced by the distribution of the physical environment. Current plant communities are not highly organized units that have co-evolved; instead they are assemblages of plant taxa resulting from large climate changes over the last 20 000 years (Hunter *et al.*, 1988). Plants respond to climate change by migrations that occur through range extension along gradients (e.g. energy, moisture) of suitable habitat and range contraction in those areas that become unsuitable. For example, Huntley & Birks (1983) documented migration rates of a few hundred to 2000 meters per year during the Holocene. One goal of the coarse-filter approach is to identify a reserve system that allows species to shift their geographic distribution in response to large-scale environmental changes. The objective of this paper is to demonstrate methods that apply a coarse-filter approach to identify gaps in the current reserve system of the *Psuedotsuga menziesii* (Douglas-fir) forest type group based on current climatic conditions and a global climate change scenario.

METHODS

Creating the envelope

We used raster maps of seven bioclimatic, two topographic, and two edaphic variables (Table 1) to define the geographic range of the Douglas-fir forest type group in the United States (Fig 1). These variables were selected because they have been used in biome distribution (Peng, 2000) and species distribution (Iverson & Prasad, 2001) models. All of the bioclimatic variables were measures of central tendency (e.g., mean, median) for a 30-year period (Table 1). For the mean growing season precipitation and growing season moisture index variables, we considered the growing season as the period between the median Julian date of the first frost-free day and the median Julian date of the first frost.

We projected each map to the Albers equal-area projection and re-sampled each map to a 3-km spatial resolution. Then we intersected the 11 maps of explanatory variables and the

Table 1 Characteristics of the maps and data used to define the geographic range of the Douglas-fir forest type group

Category	Variable	Spatial Resolution	Citation
Climatic*	Mean annual temperature Minimum annual temperature Maximum annual temperature Mean annual precipitation Mean growing season precipitation† Growing season moisture index†‡ Growing degree-days (10 °C)	1.25 arc minutes	Daly *et al.* (1994)
Topographic	Elevation Slope	3 arc seconds	USGS (1993)
Edaphic	Soil pH Available water capacity	1 : 250 000	Miller & White (1998)
Plant community	Forest type groups	1 km	Zhu & Evans (1994)
Protected areas	IUCN§ Classification of reserves	1 : 100 000	DellaSala *et al.* (2001)

*These variables are 30-year averages. The time period was from 1961 to 1990 for all variables except growing degree days which was 1951–80; †Growing season was considered the period between the median Julian date of first frost-free day and median Julian date of first frost (data from 1961 to 1990); ‡Growing season moisture index is the ratio of mean growing season potential evapotranspiration to mean growing season precipitation. Potential evapotranspiration was calculated using the Thornthwaite formula (see Akin, 1991); §International Union for the Conservation of Nature and Natural Resources (IUCN) classification I-VI.

Figure 1 Geographic distribution of the Douglas-fir forest type group in the United States.

protected areas map with the Douglas-fir forest type group map (Table 1). This created a database where each of the approximately 17 000 pixels classified as the Douglas-fir forest type group were assigned values for each of the 11 explanatory variables and a protected status. A pixel was considered protected if it fell in an area classified as International Union for the Conservation of Nature and Natural Resources (IUCN) class I-VI (see Table 2 for definitions).

We used a multivariate factor analysis to reduce the dimensionality of the explanatory variables listed in Table 1. Factor analysis is used to describe the covariance structure among many variables in terms of a few underlying, but unobserved, quantities called factors (Johnson & Wichern, 2002). Factor analysis is based on the factor model

$$\underset{(p \times 1)}{\mathbf{X}} = \underset{(p \times 1)}{\boldsymbol{\mu}} + \underset{(p \times m)}{\mathbf{L}}\underset{(m \times 1)}{\mathbf{F}} + \underset{(p \times 1)}{\boldsymbol{\varepsilon}} \qquad (1)$$

In this case, $\mathbf{X}$ is linearly dependent on the unobservable random variables $F_1, F_2, \ldots, F_m$, or common factors. The vector $\boldsymbol{\mu}$ is a vector of p means and $\boldsymbol{\varepsilon}$ represents additional sources of variation or errors. $\mathbf{L}$ is a matrix of factor loadings. The factor model implies a specific covariance structure

$$\mathrm{Cov}(\mathbf{X}) = \mathbf{L}\mathbf{L}' + \boldsymbol{\Psi} \qquad (2)$$

where $\boldsymbol{\Psi}$ is a matrix of specific variances. Each diagonal element of $\boldsymbol{\Psi}, \boldsymbol{\Psi}_i$, is $\sigma_{ii} - \sum_{j=1}^{m} l_{ij}^2$ for each $i = 1, 2, \ldots, p$ and the off diagonal elements of $\boldsymbol{\Psi}$ are zeros. There are several methods that can be used to factor the covariance matrix. One commonly used method is the principal components method. In this case, equation 2 is used and $\mathbf{L}$ is calculated based on the eigenvalues and eigenvectors of the principal components.

To implement the factor analysis each of the explanatory variables were standardized to mean zero and variance one. This was done by $x_{ip} - \mu_p/s_p$ where x_{ip} is the i^{th} observation on the p^{th} variable, μ_p is the mean of the p^{th} variable, and s_p is the standard deviation of the p^{th} variable. The component axes were orthogonally rotated using the varimax rotation (Kaiser, 1958) to help interpret the factor loading ($\mathbf{L}$).

The resulting axes represented independent factors that were linear combinations of one or more of the original explanatory variables and summarized the information contained in those variables. Because different variables had different loadings, each factor was interpreted in terms of the specific variables that had high loadings for that factor. In addition, for each factor, a factor score was calculated for each Douglas-fir forest type group pixel.

We used the first two factors to describe the ecological envelope where the Douglas-fir forest type group exists. For each Douglas-fir forest type group pixel, the factor one and factor two scores were plotted on the x-axis and y-axis, respectively. We then created a 631 by 687 cell lattice that tiled the envelope. To account for different intensities in the envelope, we used a sliding window analysis to calculate relative density for each grid cell in the lattice. The sliding window was 27 units by 27 units (Fig 2) and relative density was calculated by

$$\Delta_j = D_j / D_{max} \qquad (3)$$

where Δ_j was the relative density at the j^{th} location, D_j was the number of points in the sliding window for the j^{th} location, and D_{max} was the maximum D_j across all locations. This procedure smoothed the two-dimensional histogram of pixel values. To improve interpretations, the Douglas-fir relative density map was parsed into edge, interior, and core habitats, where edge was defined as $\Delta < 0.2$, interior was $0.2 = \Delta < 0.8$, and core was $\Delta = 0.8$.

Identifying current gaps

Following the same procedure described above and equation 3, we calculated the relative density of protected areas in the ecological envelope. To do this, we used only the pixels that were classified as protected (DellaSala *et al.*, 2001). To identify holes

Table 2 Description of IUCN categories

IUCN Category	Description
Ia	Strict nature reserve/wilderness area: protected area managed mainly for science or wilderness protection
Ib	Strict nature reserve: protected area managed mainly for science
II	National park: protected area managed mainly for ecosystem protection and recreation
III	Natural monument: protected area managed mainly for conservation of specific natural features
IV	Habitat/species management area: protected area managed mainly for conservation through management intervention
V	Protected landscape/seascape: protected area managed mainly for landscape/seascape conservation and recreation
VI	Managed resource protected area: protected area managed mainly for the sustainable use of natural ecosystems

Source: IUCN (1994).

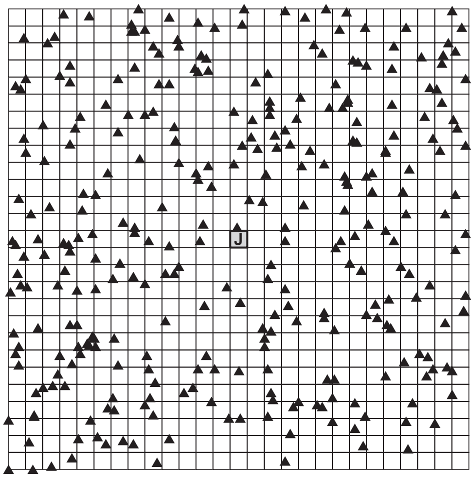

Figure 2 Example of a 27 unit by 27 unit sliding window. In this example, the central pixel is the subject pixel and denoted *j* and D_j is 306.

(gaps) in the current reserve system, we calculated the proportion of each grid cell represented by protected areas by dividing D_j from the protected area density map by the D_j from the Douglas-fir forest type group map. For discussion purposes, we arbitrarily selected areas where the quotient was less than 0.025.

Incorporating climate change

While the geographic range of a species or community can shift as climate changes, we assumed that other influences such as genetic drift and speciation, would not occur over this relatively short time-period and the ecological envelope would remain the same. For example, the temperature and moisture requirements for the Douglas-fir forest type group will probably not change much over the next 100 years. However, the geographic locations where temperature and moisture are favourable are likely to change. To incorporate climate change into this analysis we used predicted future climates of all protected areas in the western United States to determine which protected areas could have suitable habitat for the Douglas-fir forest type group in the future. Then we applied the same sliding window technique to identify what part of the ecological envelope the current protected areas would likely represent in the future.

We used the Pennsylvania State University/National Center for Atmospheric Research nested regional climate model (MM4) (Giorgi *et al.*, 1994) under a 2xCO_2 (Thompson & Pollard, 1995a, 1995b) scenario available from the Vegetation/Ecosystem Modelling and Analysis Project (VEMAP) group (Rosenbloom & Kittel, 1996) to incorporate climate change into this analysis. This particular climate change scenario was selected because change estimates for minimum and maximum temperatures were included as modelled variables. Overall, this model suggested that average annual temperature may increase by 3.9 °C and average annual precipitation may increase by approximately 31% for the coterminous United States under a doubling of CO_2. Hansen *et al.* (2001) reported a range of increases in average temperature from 2.8 to 6.6 °C and a range of increases in average annual precipitation of approximately 2–31% for the United States. We used the MM4 model only as a demonstration of how global climate change scenarios can be incorporated with the analytical techniques presented here.

The original maps of mean annual temperature, minimum annual temperature, maximum annual temperature, mean annual precipitation, mean growing season precipitation, growing season moisture index, and growing degree-days were adjusted based on predicted climate change. Each of these maps was multiplied by the corresponding change ratio map derived from the MM4 model. For maps of growing season variables, we calculated the change ratio based on predicted climate changes for June, July, and August. We used the change ratio for average June, July, and August mean temperatures to adjust the map of growing degree-days. These maps, along with the original elevation, slope, available soil water capacity, and soil pH maps, were then intersected with the map of current protected areas in the western United States (DellaSala *et al.*, 2001). This yielded maps of future bioclimatic, topographic, and edaphic variables for each 3 km × 3 km pixel currently classified as a protected area regardless of current land cover.

The next step was to apply the linear combinations from the factor analysis to the potential climate of current protected areas to identify the potential future distribution of protected areas in the Douglas-fir forest type group ecological envelope. To accomplish this step, first we standardised each variable to the same statistical scale used to define the ecological envelope. This was done by using the formula $x'_{ip} - \mu_p/S_p$, where x'_{ip} is the i^{th} observation on the p^{th} variable, μ_p is the mean of the p^{th} variable from the original data, and S_p is the standard deviation of the p^{th} variable from the original data. Next, we calculated the factor 1 and factor 2 scores by applying the linear combinations from the factor model to the rescaled values for each pixel classified as a current protected area in the western United States.

We plotted the factor 1 score on the *x*-axis and the factor 2 score on the *y*-axis and deleted any point that fell outside the ecological envelope of the Douglas-fir forest type group. Next, we ran the sliding window analysis (described above) to calculate the relative density of potential Douglas-fir forest type group habitat in current protected areas based on the climate change scenario. We then examined the physical characteristics (e.g. elevation) of the protected areas where habitats conducive to the Douglas-fir forest type group could occur. We also investigated what parts of the ecological envelope would be represented by the current protected areas.

RESULTS

Three components describing the geographic range of Douglas-fir were identified using factor analysis (Table 3). These three factors explained 84% of variance among the 11 original variables. The first factor explained 58% of the variance across all variables. We interpreted factor 1 as a composite of variables related to energy because growing degree-days had the largest loading for this factor. Elevation and the other temperature-related variables also had relatively high loadings. The negative sign of the loading for elevation is logical because temperature generally increases as

Table 3 Results and interpretation of the factor analysis based on the current climate. Variables are grouped by the weights in the rotated factor pattern. Factor 1 was interpreted as a composite of variables related to energy. Factor 2 was interpreted as a composite of variables related to moisture

	Rotated Factor Pattern		
Variable	Factor 1	Factor 2	Factor 3
Growing degree days	**0.964**	0.077	−0.040
Maximum annual temperature	**0.952**	0.164	−0.076
Mean annual temperature	**0.925**	0.341	−0.125
Minimum annual temperature	**0.835**	0.465	−0.156
Elevation	**−0.761**	−0.451	0.266
Growing season moisture index	0.148	**0.937**	−0.025
Mean annual precipitation	0.197	**0.894**	0.011
Growing season precipitation	0.300	**0.886**	−0.032
Soil pH	−0.360	**−0.649**	0.193
Slope	−0.075	0.127	**0.870**
Available water capacity	0.193	0.396	**−0.610**
Cumulative variance explained (%)	58	74	84

elevation decreases. The second factor explained an additional 16% of the variance and was interpreted as a composite of variables related to moisture. The growing season moisture index had the greatest loading for factor 2. Soil pH, growing season precipitation, and annual precipitation also had relatively high loadings. The loading for soil pH was negative which is plausible because humid areas generally have more acidic soils (Akin, 1991). Factor 3 (not used in subsequent analyses) explained an additional 10% of the variance and was most associated with slope and available water capacity.

The relative density map showed two distinct subpopulations (Fig 3a). One occurred in the cooler and drier part of the range and incorporated all of the core area. Geographically, this subpopulation coincided with the distribution of the Douglas-fir variety, *glauca* (Fig 3b). The second subpopulation was found in a comparatively warmer and wetter part of the range and is more typical of the variety *menziesii* (Fig 3a). The warmer and wetter part of the range was mostly located in the western areas of Washington, Oregon, and northern California (Fig 3b). Approximately 2000 of the Douglas-fir forest type pixels (11.8%) were classified in IUCN classes I-VI. However, most protected areas were in the coolest and driest part

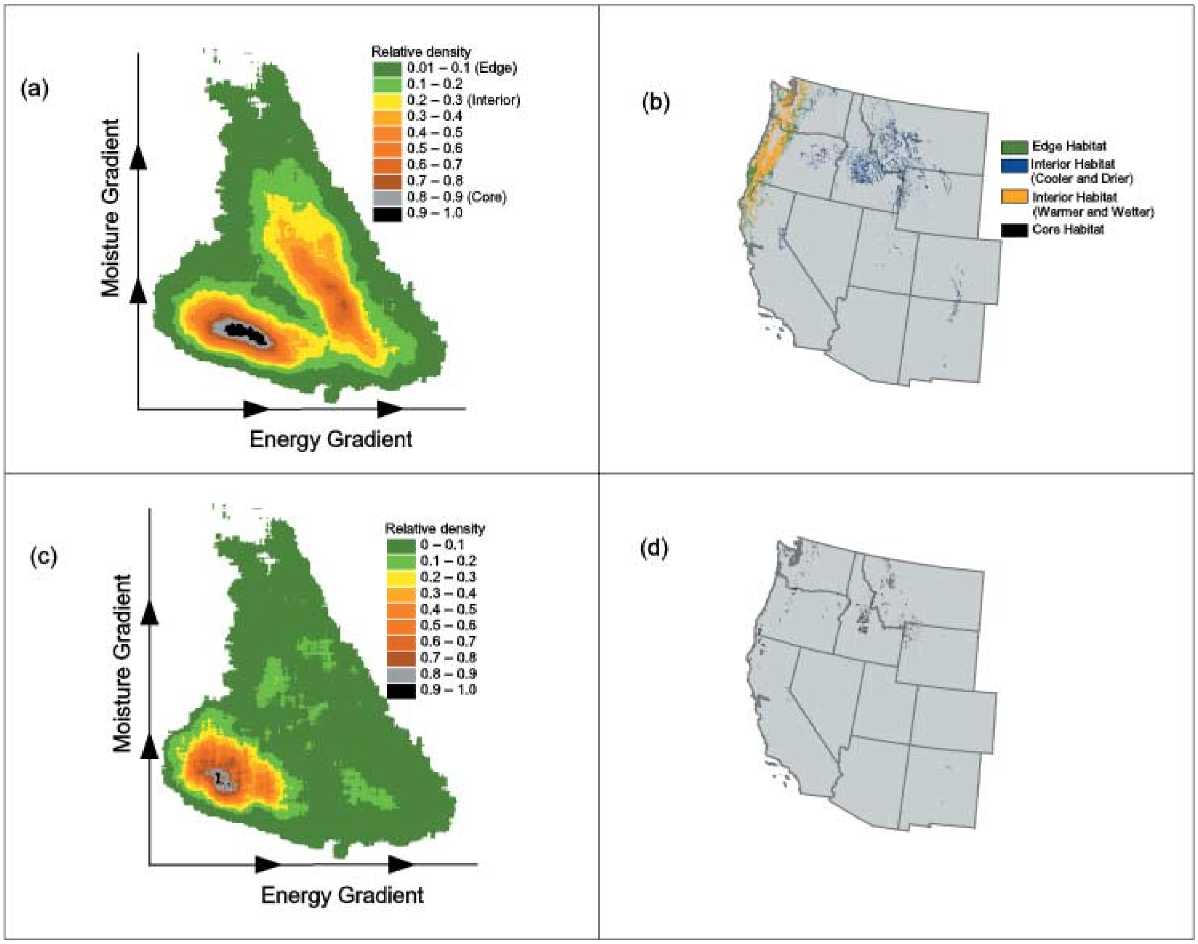

Figure 3 Relative density of the Douglas-fir forest type in its ecological envelope (a). The geographic distribution of core, interior, and edge (b) Douglas-fir forest type group habitat based on the current climate, the relative density (c) and the geographic distribution (d) of protected areas containing the Douglas-fir forest type group based on the current climate.

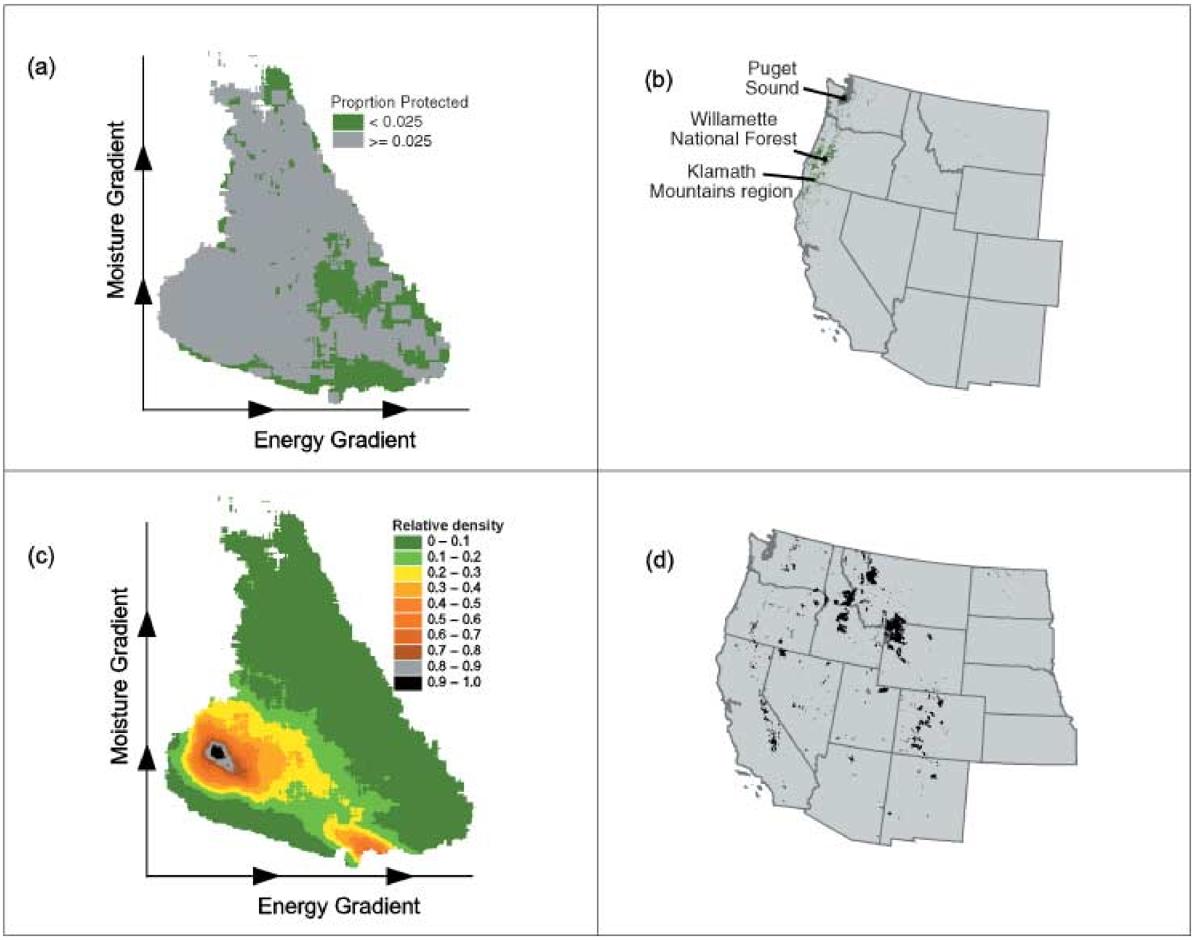

Figure 4 The distribution of potential areas for Douglas-fir forest type group reserve establishment in (a) the ecological envelope and (b) mapped based on the current climate. (c) The relative density and (d) geographic distribution of Douglas-fir forest type group protected areas based on the MM4 global climate change scenario.

of the range (Fig 3c). In geographic terms, the protected areas were mostly in Idaho, Montana, and Wyoming (Fig 3d).

Many of the areas where reserves were lacking occurred in the edge and relatively wet and warm portions of the ecological envelope (Fig 4a). These areas were concentrated in western Washington, western Oregon, and north-western California (Fig 4b). Some of the areas where conservation efforts would be beneficial are in publicly owned land such as national forests. For example, the Willamette National Forest in western Oregon has approximately 1062 km^2 of the Douglas-fir forest type that were classified as warm and wet interior habitat that were not under protection based on the DellaSala *et al.* (2001) classification. Transferring some of this area to a protected area status would fill in some of the gaps in protection. There was also approximately 1800 km^2 of the Douglas-fir forest type warm and wet habitat on private land in the Puget Sound area. Some of this area would also be a candidate for protection. Several areas in the Klamath Mountains region of southern Oregon and northern California were also candidates for protection because these areas are some of the driest parts of the edge habitat.

Based on the MM4 climate change scenario, most of the protected areas meeting the energy and moisture requirements of the Douglas-fir forest type group will be in the cooler and drier part of the range (Fig 4c). Geographically, these areas are concentrated in the Rocky Mountains but several other areas are represented (Fig 4d). The MM4 climate change scenario suggests that both temperature and moisture will increase in the western United States. One consequence of increasing temperatures is that the geographic range of the Douglas-fir forest type group may move to higher elevations. With respect to protected areas, the current reserves of the Douglas-fir forest type group are on average 1791 m in elevation. Under the climate change scenario, protected areas with suitable Douglas-fir forest type group habitat have, on average, an elevation of 2332 m. However, a substantial percentage (57.4%) of the protected areas currently containing the Douglas-fir forest type group are likely to have suitable habitats based on the climate change scenario. We suggested the Willamette National Forest as a candidate area for protection because it represented core area of the warmer and wetter habitat. Under the climate change scenario, the candidate area would potentially represent edge habitat in the wettest region of the envelope. Areas in the Klamath Mountains regions were also suggested as potential targets. Based on the MM4 climate change scenario, if these areas were protected they would represent the warmer and wetter part of the habitat in the future.

DISCUSSION

Species respond not only to climate shifts but also to other pressures that shape genetic variation. Maintaining genetic variation is an important goal of reserve systems because the long-term survival of a species depends on the availability of a wide variety of genetic material (Rajora & Mosseler, 2001). Genetic variation, for example, is influenced by natural selection, genetic drift, and speciation, which generally operate over a longer time scale than species migration (Delcourt & Delcourt, 1988). Often, disjunct or isolated populations possess unique adaptations or important genotypes and alleles because of more intense selection pressures on habitat edges (Rajora & Mosseler, 2001). Isolated or marginal habitats can be identified using the proposed methods. In fact, the areas identified as edge (Fig 3a and Fig 3b) represent marginal habitat and a true disjunct population would be isolated in the ecological envelope.

One criticism of the coarse-filter approach is that rare species can slip through the filter (Hunter *et al*., 1988). This analysis is considered a coarse filter approach. However, the same technique can be used with finer-scale data to address rare species. For example, *Cypridpedium fasciculatum* (clustered lady slipper orchid) is a rare species that exists in the Douglas-fir forest type group community (Brownell & Catling, 1987). The results from the coarse-filter analyses could be scaled down by increasing the spatial and thematic resolution for the specific areas in the Douglas-fir ecological envelope where the clustered lady slipper exists. Increasing the resolution may require more, or different, explanatory variables. Scaling down is a valid approach unless there are too few areas to identify the distribution in feature space.

This approach has shortcomings. Hunter *et al*. (1988) suggests that reserve systems should be connected by large-scale corridors. We did not deal with the issue of corridors, however, Riitters *et al*. (2002) found that forests are relatively well connected over large regions in the United States. In this paper we examined the intensity of the Douglas-fir forest type group within a two-dimensional envelope. However, this may not be adequate to represent the variation of other communities. The example presented here can be extended to three dimensions by using convex-hull algorithms to define a three-dimensional envelope and then using relative density inside the envelope. The techniques presented here can also be applied to larger-scale (e.g. forest biome) and smaller-scale (e.g. species) analyses.

Holes in the current Douglas-fir forest type group reserve system were identified based on an ecological envelope approach where the distribution of the community was defined by energy and moisture gradients. Once the holes were identified, the geographic locations where protection would be beneficial were identified. Others have used a similar approach but at a much lower spatial and thematic resolution. For example, Scott *et al*. (2001b) analysed the conservation status of four vegetation types in the western United States. They used strata based on latitude, longitude, and elevation and found that reserves were unevenly distributed both geographically and across elevation classes. In a separate analysis, Scott *et al*. (2001a) found that nature reserves were most frequently located on sites with relatively low soil productivity and at higher elevations. The results of our analysis more or less correspond with the results of Scott *et al*. (2001a) but go a step further by targeting specific areas based on several ecological factors and including climate change.

The geographic distribution of a plant species may shift as climate changes and the rate and direction of migration differs among taxa such that species associations are also expected to change (Davis, 1981; Webb, 1992). Melillo (1999) suggested that the distribution of some North American species could shift northward up to 300 miles in response to these changes. For the Douglas-fir forest type group under the MM4 global climate change scenario we found that suitable habitat will likely be found at higher elevations and that 57.4% of the Douglas-fir forest type group protected areas will likely still have suitable habitat under the MM4 climate change scenario. It is important to point out that 42.6% of the current protected areas did not have habitats in the ecological envelope under the climate change scenario but this does not mean these areas are not of interest. Other communities may migrate into these areas. To investigate the influence of climate change more fully, multiple climate change scenarios should be examined.

A reserve system that captures the variation of a community will allow the species comprising the community to adjust their geographic distributions in response to environmental change (Hunter *et al*., 1988). Here we demonstrated one method to examine how the current reserve system captures the variation of the Douglas-fir forest type group, suggest areas where reserve establishment would be beneficial, and examine the potential influence of climate change. In the United States, there are 21 major forest types groups (Zhu & Evans, 1994) and a similar approach could be used for each one. Aggregating those results would help identify gaps at national and global levels.

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